IEA Bioenergy
Technology Collaboration Programme

# IEA project Site productivity impacts of intensified biomass recovery

## literature and knowledge review

IEA Bioenergy: Task 43

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## INTRODUCTION

The global move towards sustainable energy solutions to reduce reliance on finite fossil fuel energy sources and greenhouse gas emissions, is driving demand for biomass from a wide range of sources, including forest biomass. The greatest opportunity for increased supply of forest biomass is from forest harvesting residues (Long & Boston, 2013). This is especially true in Australia, as only a small proportion of the millions of tonnes of residues produced per annum is currently utilised (Lock & Whittle, 2018).

Past “clear and burn” silvicultural practices that almost completely removed above ground biomass have demonstrated site productivity losses, in some cases catastrophic, particularly on low fertility sites, as compared to removal of stem wood products only (Isaac & Hopkins, 1937; Woods, 1990). Concerns have subsequently been raised about potential productivity impacts of any forest biomass removals additional to log harvesting (Egnell & Valinger, 2003; Nambiar, 1996). With limited understanding of where critical points are on how intensive a biomass recovery plantation managers can carry out while sustaining long-term site productivity, forest managers tend to be conservative with the intensity of forest biomass recovery, limiting biomass availability at scale.

## AIMS

- Carry out a comprehensive literature and knowledge review on research on short to long-term site productivity impacts of different levels of biomass recovery on forest and plantation sites
- Produce a peer reviewed journal article
- Frame a future long term research plan to address key knowledge gaps and better equip forest and plantation managers to plan and deliver biomass supply with a strong understanding on how much can be extracted within acceptable and sustainable long term site productivity.

## LITERATURE REVIEW

There were two major changes to global forest management during the 1990s which have impacted the potential utilisation of forest biomass: the move away from managing forests with a primary focus on timber production to broader management of ecosystems (sustainable forest management (SFM)); and, an increased focus on renewable energy, including biomass, to reduce dependence on imported energy sources and reduce greenhouse gas emissions(Stupak et al., 2007). While it is recognised that logging residues can provide ecosystem services other than those related to growth of future tree rotations, the focus of this literature review is only on the impacts of logging residue recovery on site productivity.

The definition of site productivity used in this review is that by Skovsgaard and Vanclay (2007): “Forest site productivity is the production that can be realized at a certain site with a given genotype and a specified management regime. Site productivity depends both on natural factors inherent to the site and on management-related factors”. Logging residue can impact site productivity through retention of soil moisture, organic matter and nutrients, and protection of the soil from compaction caused by harvesting machines (Udali et al., 2024). Logging residue typically contains a high proportion of the nutrients in the above ground biomass of a plantation or forest (Hopmans & Elms, 2009; Merino et al., 2005; Vos et al., 2023; Węgiel et al., 2018).

The impacts of logging residue recovery on site productivity are dependent on a range of interacting factors, including the proportion of the total residues recovered, the proportion of each residue component recovered (stem wood, branches, leaves/needles, bark), harvest intensity, site soil fertility, tree species and genetics, and rotation length. The impact of logging residue recovery on site productivity has mainly been evaluated through measurement of tree growth using field trials. This approach may introduce additional random elements (for example variations in weather patterns or damage from biotic or abiotic causes), particularly as the trials are often conducted over multiple decades and in some cases multiple rotations.

## Proportion of residue recovered

The proportion of total logging residues recovered can vary greatly. While whole tree harvesting (WTH) is often considered to maximise logging residue recovery, retention of logging residue resulting from breakage of crown tops and branches during felling, handling, primary transport and processing can be considerable (Thiffault et al., 2015). WTH logging residue recovery rates reported in the literature are mostly between 50% and 60% (Hytönen & Moilanen, 2014; Kizha & Han, 2015; Klockow et al., 2013; Thiffault et al., 2015). The highest logging residue recovery rates (over 70% recovery) have been reported where residues are piled during harvest (fuel-adapted harvesting), such as is commonly practiced in Nordic countries (Nurmi, 2007; Peltola et al., 2011; Thiffault et al., 2015). However, as this material is typically left to dry infield or at roadside over summer, the final proportion recovered can be considerably lower, mainly due to losses of fine material. The lowest logging residue recovery rates (typically 30%-40%) are from conventional cut to length at the stump harvest (CH) operations as the scattered distribution of the logging residues reduces the operator’s ability to collect them (Strandgard & Mitchell, 2019; Thiffault et al., 2015). The upper limit of operational logging residue recovery is limited by economic and environmental considerations. These include leaving unusable, soil-contaminated residues onsite (Pettersson & Nordfjell, 2007) and distributing residues along harvest vehicle paths to reduce soil compaction (Han et al., 2006), which can have a significant impact on site productivity if not minimised (Ampoorter et al., 2011).

While a wide range of logging residue recovery rates has been reported from harvest operations, studies of the impact of logging residue recovery on site productivity have overwhelmingly been based on testing the impact of 100% logging residue recovery (Corbeels et al., 2005; Egnell, 2016; Egnell & and Leijon, 1999; Helmisaari et al., 2011; Mendham et al., 2014; Proe et al., 1999; Rocha et al., 2016; Węgiel et al., 2023). To achieve this level of recovery requires manual collection of residues, which would be uneconomic operationally. In some cases, the impact on site productivity of burning of logging residues has been used to impute the effects of logging residue recovery. While these studies have generally concluded that recovery of all logging residues can significantly reduce site productivity, the applicability of these findings to operational logging residue recovery is likely to be limited. For example, Wei et al. (2020) found that retaining the quantity of logging residue expected from a WTH operation in a second rotation *P. contorta* stand resulted in height and diameter growth at age 19 that was significantly greater than that for a stand with all residues removed and was not significantly different from that of a stand with the quantity of logging residue expected from a CH operation.

Further research is required into the impacts on site productivity from logging residue recovery rates that reflect operational practices.

## Soil fertility

The strongest relationships between the proportion of logging residue recovered from a site and changes in site productivity have been observed on sites with low soil fertility. Gonçalves et al. (2007) found that standing volume ($m^3$ $ha^{-1}$) at age 8.7 years for a second rotation *Eucalyptus grandis* plantation on a low fertility site in Brazil was reduced by 30% for trial plots where all above ground biomass was removed at the end of the first rotation compared with the growth on trial plots where the logging residue was retained. In a study at a low fertility second rotation site in the Congo planted with Eucalyptus PF1 clonal material (a natural hybrid *Eucalyptus urophylla* x *Eucalyptus grandis*), Laclau et al. (2010) found that removal of all residues and the litter layer resulted in the lowest standing volume at age seven (96 $m^3$ $ha^{-1}$), while the highest age seven standing volume was observed for the treatment where double quantities of logging residue were applied (164 $m^3$ $ha^{-1}$). Similarly Mendham et al. (2003) found that doubling the logging residue quantity significantly increased tree growth on a low fertility site in a second rotation *Eucalyptus globulus* plantation, while on a high fertility site, tree growth was unaffected by the quantity of logging residue (zero, normal or double quantities). In studies of coniferous species, Mason et al. (2012) found that the greatest growth response at age ten of Sitka spruce on CH sites compared with that on WTH sites occurred on the lowest fertility site and Egnell (2016) observed reduced growth at a number of Norway spruce trials on lower fertility sites following reductions in retained logging residue levels, while at two high fertility sites in Finland, no significant difference was found between the mean stem volumes ($m^3$) of 22-year-old Scots pine trees on WTH and CH treatment plots (Saarsalmi et al., 2010).

However, the relationship between site productivity and levels of retained logging residue on low fertility sites is not universal. Egnell and and Leijon (1999) found that increased recovery of logging residue reduced basal area growth of Norway spruce on both high and low fertility sites and for Scots pine on a high fertility site. A reduction in the quantity of logging residue retained has also been associated with an increase in the growth of Scots pine on low fertility sites (Egnell, 2016; Egnell & and Leijon, 1999) whereas a study in New Zealand second rotation *Pinus radiata* plantations across three sites of varying fertility (low, moderate and high fertility), found no significant difference in final harvest stand volume between CH and WTH treatments at all sites (Garrett et al., 2021).

The above studies excluded the application of fertiliser which is routinely applied at time of planting in many parts of the world (Smethurst, 2010), and which may have compensated to some extent for nutrient losses resulting from logging residue removal.

## Thinning operations

Thinning operations involve partial removal of the growing stock during a rotation, typically to remove trees of poor form or vigour and promote the growth of the retained trees. Logging residues have been seen as a potential source of extra income from thinning operations (Hytönen & Moilanen, 2014), however, as with clearfell operations, concerns have also been expressed as to the potential for reduced tree growth following logging residue recovery (Ranius et al., 2018).

In one of the largest published studies of the impacts of logging residue recovery from thinning operations, Helmisaari et al. (2011) compared the effects of WTH and CH, with and without fertilisation, on the growth of Scots pine (14 sites) and Norway spruce (8 sites) trees across Finland, Sweden and Norway. The study was conducted over a 20-year period. In the ten years after first thinning, mean annual volume increment ($m^3$ $ha^{-1}$ $yr^{-1}$) was significantly less on the WTH plots than the CH plots for Norway spruce while there was no significant difference between the Scots pine plots. Some plots of both species were thinned again ten years after the first thinning. Mean annual volume increment over the next ten years for the second thinned Norway spruce was significantly less for the WTH plots than for the CH plots, while tree growth on the second thinned Scots pine CH and WTH plots were not significantly different. For the Scots pines plots thinned once, the mean annual volume increment of the WTH plots for the entire 20-year measurement period was significantly less than that for the CH plots. While these results suggested recovery of thinning logging residue could significantly reduce subsequent growth of Scots pine and Norway spruce trees, there were confounding factors in this trial, including wide ranges amongst the sites in terms of their age, stocking, thinning intensity and site index, that complicate interpretation of the results. This was reflected in the wide range of growth responses amongst individual trial sites in this study. In addition, the Norway spruce plots where the normal level of post-thinning fertiliser was applied only exhibited a significant difference in mean annual volume increment for the second thinned WTH and CH plots.

While the study by Tveite and Hanssen (2013) agreed with the findings of Helmisaari et al. (2011) for Norway spruce thinning with post-thinning growth for the WTH sites being found to be significantly less than that for the CH sites over a period of 25 years, they found no significant difference between mean post-thinning growth rates for Scots pine CH and WTH plots over a period of 20 years. The site and stand characteristics in this study covered a narrower range than those in the study by Helmisaari et al. (2011), however, the authors recognised that their results were likely to have been affected by confounding factors and recommended that a meta-analysis be performed to identify the effect of site factors on Scots pine and Norway spruce growth responses to differing levels of logging residue removal during thinning.

In studies outside Europe, Carlyle (1995) found no significant difference in basal area growth over four years following the-first thinning at age 10 of a *Pinus radiata* plantation in South Australia, between WTH sites where all logging residues had been manually removed and those on CH sites. Similarly, Huong et al. (2020) found no significant difference in diameter increment in an *Acacia auriculiformis* plantation in Vietnam thinned at age 4 between trees on the trial site with all residue and leaf litter removed compared with that of trees on a trial site where residue and litter were retained.

The study results reviewed in this section suggested that the magnitude of the effect of residue removal on tree growth may vary between tree species. However, in the studies cited, the WTH residue treatment included manual removal of as much residue as possible. With the exception of the trial in Vietnam, this does not replicate operational practice. Similarly, the effect on tree growth of routine post-thinning fertiliser application reported by Helmisaari et al. (2011) suggested that further research was required comparing the tree growth response of retention of levels of logging residue representative of operational CH and WTH thinning practices combined with routine fertiliser application levels.

### Proportion of each residue component recovered/retained

As many forest and plantations soils are deficient in nutrients required for tree growth, particularly nitrogen and phosphorous, the main mechanism by which retention of logging residue is believed to affect tree growth is through the release of nutrients from residues by leaching and decomposition (Helmisaari et al., 2011; Ouro et al., 2001). The leaf or needle component of logging residue generally has the highest concentration of macro-nutrients (nitrogen, phosphorous, potassium, etc), with the exception of calcium, which typically has the highest concentration in bark (Hopmans & Elms, 2009; Merino et al., 2005; Węgiel et al., 2018). Leaves, needles, twigs and bark are generally considered to be undesirable for use as boiler fuel as they can increase the production of noxious gases and aerosols and cause boiler slagging and corrosion (Kuptz et al., 2019). In Nordic countries, logging residues are normally left stacked on the cutover or piled at roadside to dry over summer. Nilsson et al. (2018) found that this practice resulted in approximately one third of the nitrogen and phosphorous in the logging residues being retained on site, while Hernández et al. (2009) found that four months after-harvest of an *E. dunn*ii plantation in Uruguay, the eucalypt leaves in the logging residue had lost approximately 40% of their mass and 30% of their nitrogen and phosphorous.

### Mechanisms relating logging residue recovery and site productivity impacts

Short-term (<5 year) impacts of logging residue recovery on tree growth have been found to be limited as the nutrient requirements of young trees during this period can be satisfied by soil reserves. Other potential benefits of residue retention on initial tree growth have been suggested, including reduced soil evaporation and weed competition, increased soil temperature and protection from weather extremes. The impact of non-nutritional effects of logging residue appears to be limited and site dependent. Smethurst and Nambiar (1990) found that while residue removal increased soil temperature and evaporation it did not affect growth of *P. radiata* seedlings during the first three years on a site in SE Australia whereas growth of Sitka spruce seedlings in Great Britain was found to be improved in one study from increased soil temperature related to residue removal (Mason et al., 2012) and in another study on a particularly windy site from reduced wind speed at 30cm related to residue retention (Proe et al., 1994).

The majority of studies into the impact of logging residue recovery on tree growth have concluded that observed growth declines in the medium to long term were the result of the removal of nutrients, in particular nitrogen, contained in the residue. The study by Helmisaari et al. (2011) supported this contention as they found in most cases post-thinning tree growth was the same for sites with residue retained and those where nutrient removal in residues had been compensated through fertiliser application.

As noted above, the impact of residue recovery on tree growth can vary between species. For example, while a number of studies found that residue recovery can reduce the growth of Norway spruce, the impact on other species, such as Scots pine and Lodgepole pine, was less clear. In the case of Scots pine and Lodgepole pine this may be related to their superior ability to extract nitrogen from the soil and use it efficiently for growth when compared with species such as Norway spruce. (Bothwell et al., 2001; Nilsson et al., 2019).

Rates of leaching and mobilisation of nutrients from the litter layer, logging residue and upper soil have been found to be in excess of the requirements of seedlings in the first few years after establishment (Smethurst & Nambiar, 1990). There has been little research into the fate of these nutrients, however, Smethurst and Nambiar (1990) suggested that a proportion of them may move to deeper soil layers. This may explain observations in a number of studies where residue was retained, of increased growth responses 5 to 10 years (or later) post-establishment, as this would be when the tree roots were able to exploit resources from deeper in the soil profile. However, this is an area where more research is required to determine whether leached nutrients are retained in deeper soil layers and, if so, whether they impact tree growth.

### Current rules and regulations defining minimum logging residue retention levels

Many countries have adopted sustainable forest management principles either as signatories to a global agreement, such as the Montreal Process, or through adoption of a forest certification scheme, such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). While these agreements and schemes do not specify minimum levels of logging residue retention, they have a role in regulating the recovery of logging residue through a high-level requirement that harvesting activities are conducted so as to maintain the long-term productive capacity of forests and plantations. While the high-level requirement does not refer to logging residue retention, in many instances it has been interpreted operationally as requiring the retention of the majority of the logging residue.

Titus et al. (2021) in a review of logging residue recovery guidelines from around the world identified 32 guidelines covering 43 jurisdictions in the USA, Canada, Europe and Japan with the majority being from individual US states. While the guidelines varied widely in their details, in general, they specify areas where logging residue recovery is not recommended (sensitive and low nutrient sites) and specify minimum proportions or quantities of fine and coarse logging residue to be retained.

Thiffault et al. (2014) proposed an approach to identify sites potentially suitable for logging residue recovery that could achieve the sustainable forest management goal of maintaining long-term forest productive capacity without the rigidity imposed by the forest management guidelines that specify minimum retained levels of logging residue. Their approach involves identifying indicators of site suitability for logging residue removal that can be used in planning logging residue harvest operations. This approach should be examined to determine its suitability for application outside Canada.

## CONCLUSION

There is considerable evidence from published studies that the productivity of sites growing Norway spruce can be reduced in both the short- and long-term following removal of the majority of the logging residue left from the previous rotation or thinning operations. This effect has been observed on both low and high fertility sites. Multiple short rotations with removal of the majority of logging residue at the completion of each rotation have also been found to reduce the site productivity in eucalypt plantations. However, the growth of several species, including Scots pine, Lodgepole pine and Radiata pine appears to less affected by logging residue removal with some studies finding no effect on growth even on low fertility sites. This may be related to the superior ability of these species to extract and use nitrogen from the soil.

Further generalisation of the results of published studies into logging residue recovery on tree growth is limited due to the complexity of interactions between the proportion of logging residue retained and its characteristics, tree species, soil characteristics, silvicultural practices and climatic conditions. Many studies were also unrepresentative of operational practices as they involved removal of the majority of logging residues, whereas in operational practice up to 50% of the logging residues could retained. The small number of trials that have examined the impact of partial logging residue retention have found tree growth differences between partial and full logging residue retention to be small or non-significant. Further research is required into the effects on growth of retention of levels of logging residue typically found following harvesting operations as well as the potential for compensation of nutrients removed in logging residue through routine fertiliser applications at time of planting and through a rotation.

There is a need for further research into the mechanisms by which retained logging residues can increase tree growth, as studies have shown that leaching and mobilisation of nutrients from logging residue and the litter layer is high soon after establishment, resulting in loss of nutrients in excess of seedling requirements down the soil profile. One potential explanation is that the nutrients are immobilised in deeper soil layers which may explain in part why growth impacts of logging residue retention have been observed in many studies to become significant later in the rotation.

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